COST COMPARISON BETWEEN A JOB SHOP, MACHINING CENTER AND CELLULAR MANUFACTURING SYSTEM

by

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1. INTRODUCTION

Thirty years ago, the United States had products that the rest of the world did not have. So the United States could provide leadership in many areas of manufacturing without much effort. Today, things are different as new technologies are easily transfered and accessible to other countries. Many of them are now not only able to catch up the technological slack, but they have also out-performed the United States in terms of producing manufactured goods with their relatively cheap labor and manufacturing capabilities. In order to regain United States's global competitiveness through improved quality, flexibility and cost efficiency, top management needs to take a hard look at its manufacturing processes and systems [1]. This implies that the potential benefits derived from such advanced technologies as CAD/CAM, robotics and manufacturing cells cannot be overlooked. But it led many people to believe that manufacturing automation would solve all our problems including cost reduction and productivity. Lawrence Michaels said this perception is not true, technologies sometimes can be a trap [2]. Examples of companies that implemented fully integrated flexible manufacturing systems and failed are numerous. One of them is the John Deere Tractor Company at Waterloo, Iowa, which applied FMS and found that the control sequence was too complex for their software to handle. The project failed after a $20 million investment and two years of debugging their software [3]. Thus the perception that the automated manufacturing system is the key to all problems should be reexamined.

This paper is not intended to discourage managers from applying automated system totally, but instead it is to point out that managers should view automated manufacturing system from a new perspective and not judge a system based on its technical sophistication [2]. This paper will also encourage managers to look into the potential of combining partially automated, simpler and less expensive manufacturing systems in conjunction with a just-in-time inventory control system or maybe consider part redesign as an alternative for solving their manufacturing problems. The key to achieving higher productivity is through some form of automated manufacturing system, production simplification, management techniques and not through sophisticated technology alone. But before we go on, an overview of the present problems associated with selecting manufacturing systems, the development of manufacturing system, and how managers currently select and justify their automated system will be first discussed.

2. PROBLEMS

Flexible Manufacturing Systems (FMS) and Computer Integrated Manaufacturing (CIM) work. Table 1 shows their performance level achieved by some U.S. users. They are impressive. 77 percent reduction in processing time, 66 percent saving in factory floor space with 30 percent of the original machine tools and 23 percent of the labor. But less than a handfull of companies could afford such systems. Some who could afford failed to put the entire system into working condition. Most companies have desires to use either FMS or CIM but face the problem of how to justify them. These managers are confused as to how they should automate their factories. There are also some managers who "wait and see" still.

Table 1: Benefits of Flexible Manufacturing System (4, p. 34)

	Prior method	FMS	Improvement	Range of improvement
Machine tools	29	9	70%	60-80%
Direct labor (people)	70	16	77%	60-88%
Number of setups	13	5	50%	10-75%
Processing time (days)	18.6	4.2	77%	30-90%
Floor space (sq. meter)	1600	600	66%	30-80%
Product cost	$2000	$1000	50%	25-75%

The problem of managing automation is tremendous. American managers are often critized for being too cautious, too slow in using new manufacturing technologies as compared to their competitors in Europe or Japan. Managers and engineers alike blamed this on many factors: the cost accounting system is not right, the capital budgeting procedure is not appropriate or because indirect benefits of new technologies are impossible to be quantified, etc (5). What was not mentioned often enough is that their problem is actually a management problem. Three of them will be discussed in this paper. They are:

a. Technological traps.

b. Myopic approach.

c. Knowledge gap.

2.1 Technological Trap

The rapid evolution of Japan into an industrial giant makes people envious and wish they could learn the Japanese manufacturing "secrets". These people rationalize that Japanese factories are ultra-sophisticated, peopled by robots, and is a prototype of the "factory of the future" [6]. Thus there was a rapid push in the United States for sophisticated manufacturing automation by ambitious vendors, researchers, professional societies and managers in the 1970's and early 1980's to match their Japanese competitors. Most managers and engineers were eager to build a factory of the future and thought it is a universal solution to all their manufacturing problems.

Of course the Japanese success was aided through a wide spread use of robots, computers and advanced machine tools. But the application of a variety of less glamarous practices and management techniques such as simpler part design, just-in-time inventory control system and workers' training programs were overlooked. American mamagers were aiming for an advanced, flexible, unmanned, paperless and complex manufacturing system. In other words, the United States was interested in building a "factory of the future" rather than a factory of today running the way it should be.

2.2 Myopic Approach

As advanced technologies like robotics, aritificial intelligence systems, expert systems, automatic storage and retrieval systems are costly equipment, they would increase the payback period of such investments. A survey shows that most American firms expect their investment to have an average payback period of 2.91 years [5]. Once an automated system does not satisfy this short payback period, the project is rejected. This is unrealistic as most automated systems cost at least one hundred thousand dollars and they need more than 2.91 years to recover all the investment costs. Thus, managers could not use emerging, useful technologies and continued to use existing out-dated machines for their manufacturing processes.

2.3 Knowledge gap

Promotion to top American corporate positions has traditionally favored people in finance, marketing, accounting and law [7]. These managers tend to worry more about the return for their stockholders than investing in capital equipment and in training their workers. The best managerial talents meanwhile went into the fast lane at Wall Street and are not involved with direct manufacturing.

The rapid evolution of new technologies has also created a sizable knowledge gap among both manufacturing and financial professionals.

3. HISTORY OF AUTOMATION

Until the 1950's, the automation of manufacturing processes had been limited to mass production systems only. These systems were often referred to as "transfer line systems" as parts are transported between work stations. The transfer-line systems were designed for a single product with a high production volume. They were highly efficient and were known for their high utilization of machines. Production in small quantities was uneconomical for such systems.

Since the 1950's, the demand structure for metal parts, which account for 30 percent or more of the GNP of many industrialized countries, has changed to more diversified products creating the need to produce a variety of products in smaller quantiites. The answer to this problem came with the invention of numerical control (NC) machines at the Massachusetts Institute of Technology in the late 1950's. With the advent of NC, the control of a machine was taken away from an operator and made automatic by information stored on a punched tape. NC machines are flexible to produce a variety of parts in the low to medium production capacity. However NCs require long set-up times and high programming skills.

Later, Computer Numerical Control machine (CNC) was developed, CNC replaced the punched tape control system with core memory and magnetic disk.

Computers were used in 1960's to control the operations of several NC machines but not material handling. Such a system was called Direct Numerical Control (DNC). When material handling was integrated and synchronized with the manufacturing operation, the system was called Computer Integrated Manufacturing (CIM). This happened in the late 1960's and 1970's. Robots, sensors, bar codes and artificial intelligence system began to be used in factories during this period.

All of those technologies can perhaps be explained chronologically except for Group Technology (GT). Group Technology was developed in the USSR following World War II [5]. The concept involved grouping parts into part families having similarities in their physical shapes and sending them through a group of machines to be processed. This procedure cut down the processing and waiting time for various parts because the number of machine set-ups were minimized. A GT factory thus consisted of cells of machines devoted to part specialization.

One manufacturing system based on Group Technology is the cellular manufacturing system. It consists of a group of people operating on a number of machines (usually NC machines) which, taken together are capable of all the machining operations necessary for a desired part. Manufacturing cells could be arranged in an L or U-shape fashion as shown in Figure 1 and 2 respectively. The whole idea behind this form of production is to allow parts to be made as they go through the cell.

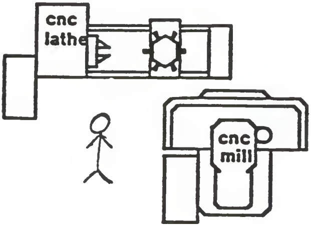

Figure 1: An L-shaped manufacturing cell.

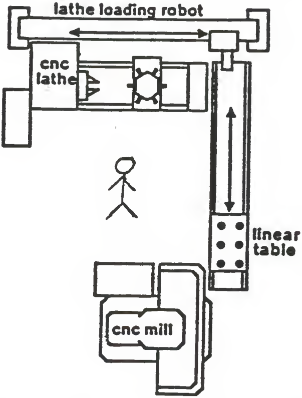

Figure 2: A U-shaped manufacturing cell.

The idea of Flexible Manufacturing System (FMS) emerged in the 1960's and it was also based on the concept of Group Technology. Basically, a FMS is made up of several manufacturing cells that have been linked together and under the total control of a supervisory computer. Thus the production, material handling, inspection, scheduling and design were linked with an on line inter-factory communication network. The first FMS installation in the United States appeared in about 1967. Figure 3 illustrates a typical FMS configuration.

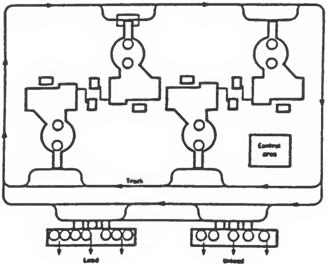

Figure 3: A Flexible Manufacturing System (FMS).

The definition of FMS is not well established. It could mean different things to different people. Raju and Karlson [8] defined FMS as a process facility under total computer control with an automated work flow system to produce a variety of parts in small batches and in non-sequential order, according to a predetermined schedule. In simple terms, FMS is defined as a system providing mass production economics in a batch production environment.

In the 1970's and early part of 1980's, there was a great push for total integrated systems such as FMS. During the same period, research and development in artificail intelligence, expert systems, robot vision, bar codes, parallel processing, sensors and fifth generation computers have prompted engineers towards designing unmanned, paperless, and totally flexible manufacturing factories.

A recent trend shows that many companies that had long considered FMS technology, are now opting for for something smaller, simpler and cheaper [4]. Managers now consider buying manufacturing cells and even stand-alone computer numerical controlled (CNC) machine tools.

In the United States, nearly 95 percent of the production machines used belong to the pre-NC technology [5]. The remainder, 4 to 5 percent consist of NCs, CNCs, flexible manufacturing systems and a few manufacturing cells. Efforts had been made by companies to integrate these islands of automation through Manufacturing Automation Protocol (MAP) communication standards. Some 400 equipment vendors in the US are also committed to making MAP compatible products in the future.

The US National Research Council reported that in 1982, there were 25 FMS installations in this country, Western Europe and Eastern Europe each had 25 and Japan had 40 FMS [9]. In 1985, about 50 FMS were reported to be operating in the US.

Figure 4 shows the distribution of FMS installations in each country. The automobile industry appears to be the main user of FMS in both the United States and Europe. In Japan, the automobile is the smallest user of FMS, while the machine tool industry as the largest user of FMS [9].

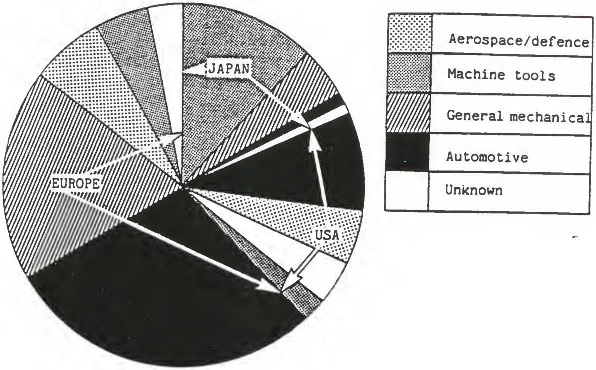

Figure 4: The distribution of FMS installation in each country (9, p. 79)

4. PRESENT METHOD

Managers and engineers can use a variety of methods for justifying their automation proposals. These methods could be based on intuition (non-numeric methods), economic analysis (numeric methods), expert systems and selection guidelines.

4.1 Non-numeric models

Under non-numeric models, selection and justification of manufacturing investment proposals are made under the influence of the individual's intuition. Vigorous economic analysis are bypassed. Four different models are commonly used: sacred cow, operating necessity, competitive necessity and product line extension.

a. Sacred cow

Under the sacred cow model, the initiation and justification of a project is purely based on the suggestion of a senior, experienced or powerful official in the organization.

b. Operating necessity

The initiation of a project is purely to keep an important system operating. For example, in the designing department, a Computer Aided Design (CAD) is proposed. The basic issue examined here is wheather the new CAD system is worth maintaining at the estimated cost of the project.

c. Competitive necessity

In the competitive necessity approach, managers decided to update their manufacturing system or a sub-system in it just to keep up with competitor's technology.

d. Product line extension

Whenever a new product is added into existing production, managers install new a designing or manufacturing system just for that new product.

4.2 Numeric models

In numeric models, vigorous economic analysis are used. Generally, numeric models could be further classified into two major categories depending on the number of criteria the user is using. The first category is called a financial model. It uses a single-value financial criterion for decision making. The payback period, Return On Investment (ROI) and Net Present Value (NPV) are the most commonly used methods.

The second category is called a scoring model as multiple criteria are used to evaluate several alternatives. These methods include the profile chart, symbolic scoreboard and linear additive model. Advantages of using such models are multi-criteria capability, simplicity, ease of use and understanding. On the other hand, it creates a temptation to include a large number of factors in the decision criteria. Choosing a comprehensive set of mutually exclusive criteria can also be a problem.

Finanacial models will be discussed first followed by scoring models.

a. Payback period

The payback period method is the most frequently used method. Surveys show that 65% of managers used this approach [12] for making manufacturing system investment decisions.

The payback period calculates the time for the total expected savings to be equal to the cost of equipment installed. American managers expect a relatively short payback period of 2.91 years.

b. Return On Investment (ROI)

The ROI is the second most frequently used method for justifying equipment investment projects. Reports show that 26 percent of the managers used this approach [11].

The ROI calculates the discounted rate (interest rate) at which the expected discounted savings equals the investment project cost.

c. Net Present Value (NPV)

Net Present Value is the third most frequently used method in justifying automation projects. 5% of the managers used it.

The NPV calculates the sum of the expected savings from a project discounted at a predetermined interest rate minus the project cost

Scoring models make use of multi-criteria decision making. Some of the more frequently used models are as follows:

a. Profile chart

Figure 5 illustrates a profile chart that utilizes a simple scoring system to indicate how well a particular alternative meets each criterion.

	Alternative A				Alternative B			
Decision factor	-2	-1	1	2	-2	-1	1	2
Effect on annual sales			X			X	X	
Manpower avail		X	X		X			
Product quality		X					X	X
Investment cost			X					X
Inventory reduction			X	X		X	X	X

Figure 5: A Profile Chart.

Each criterion is evaluated according to the scale below:

-2 = saving less than $100,000

-1 = saving between $100,000 to $200,000

1 = saving between $200,000 to $400,000

2 = saving more than $400,000

A greater or smaller number of rating scales could be used in this case. Uncertainty was indicated by showing 2 or more values in the chart. The purpose of a profile chart is to indicate visually the difference in levels of savings for each criterion among the alternatives. Profile charts make no attempt to indicate the relative importance of various criteria being used. The chart merely provides the decision maker with a visual summary of information used in choosing between alternatives according to his or her subjective judgement.

b. Symbolic scoreboard

A symbolic scoreboard is a special type of profile chart. In a scoreboard, different colors or symbols are utilized to show the relative desirability of 2 or more alternatives for each criterion of interest. Figure 6 shows an example of the symbolic scoreboard.

Decision factor	A	B	C	Do Nothing
Cost	$115,000	$338,950	$32,000	$0
Reduc. in design time	60%	67%	50%	0%
Lead time	▩	▨		
Flexibility	▩	▨		
Quality	▩	▨		

Excellent ▩ Good ▨ Poor ☐

Figure 6: A Symbolic Scoreboard.

It is sometimes difficult to assign ratings to alternatives because the criteria used are ambiguous. Another drawback is that decision makers may be tempted to equate the best alternative with the one having the largest number of desirable characteristics.

c. Linear additive model

The linear additive model is a decision making tool that aggregates information from unique, independent criteria in a linear fashion to arrive at an overall score. The alternative with the highest score is most preferred. The general form of the model is:

$$V_j = \sum_{i=1}^{n} w_j x_{ij}$$

where V_j = the score of the j th alternative.

w_i = the weight assigned to the i th decision criterion.

x_{ij} = the rating assigned to the i th criterion for alternative j.

An example of the linear additive model is in Figure 7.

w_j	Decision factor	Do Nothing	Purchase a new system
1.0	Annual cost of ownership	1.0	0.7
0.5	Flexibility in types of jobs	0.8	1.0
0.8	Ease of training and operation	1.0	0.5
0.7	Time saving per part	0.7	1.0
	V_j	2.69	2.30
	Normalized V_j	1.00	0.96

Figure 7: Linear additive model for machine tool replacement.

In this method, the decision maker assign ratings to the decision criteria on a ratio scale of 0.0 to 1.0. The highest ranked criterion is rated 1.0, and the second ranked criterion is assigned a rating of 0.8 if it is perceived to be 80% as important as the highest ranked criterion. For example, the current machine tool (or do nothing) may be assigned a 1.0 for the annual cost of ownership criterion, while the new machine tool may be assigned a 0.7 rating because it is seven-tenths as desirable as the current asset in terms of this criterion.

Another form of justification technique currently available is the expert system.

4.3 Expert System

An expert system (ES) is a computer program that attempts to solve a difficult and complex problem usually solved only by applying human expertise. Typically, there are three components in an ES: 1. A knowledge base which consists of rules, facts etc, utilized by experts to solve a particular problem; 2. An inference engine which contains the line of reasoning used by an expert to arrive at a conclusion in view of 1; and 3. a dialog system by which ES users can communicate with the knowledge base through the inference engine.

The number of operational ES used for financial justification in the manufacturing and service industries is increasing. One ES for such a purpose is called XVENTURE developed by Sullivian at the University of Tennessee and LeClair at the USAF. This ES makes use of six issues that are vitally important in investment decisions involving advanced manufacturing technology, then the ES links these issues into a rule basis that represents the expertise of a single expert. Table 2 represents the 6 basic issues and responses in XVENTURE.

Table 2: The 6 issues and responses in XVENTURE
(11, p. 7-5)

1. Today's investment options must be effectively managed for future growth. Which of the following best describes the investment opportunity being evaluated?
   1 The technology is immeadiately available for a price.
   2 The technology window will open for years and is not proprietary.
   3 The technology window will be opened for years and is proprietary.

2. The firm's technology plan should match its business plan for the next five years, otherwise success of new technology is questionable. Select one of the following which best reflects your technogy/business match regarding this investment.
   1 The two plans are not likely to ever agree
   2 They do not agree now but may in 1-2 years
   3 They do agree now but may not in 1-2 years
   4 They match perfectely with no changes foreseen

3. Consider your firm's present cost accounting system. How would you rate prospects for a future accounting system that considers direct and indirect labour cost to be fixed and a flexible manufacturing system investment to be variable cost based on utilization?
   1 Absolutely not possible during the foreseeable future
   2 Management is reluctant but will give the concept a fair review
   3 Support is excellent and such is being developed.

4. A complex investment tends to be strategic and long-term in nature, while a simple investment is tactical and short-term in outlook. Choose which statement best describes the investment's complexity and technological/environmental uncertainty.
   1 Investment is complex and there is considerable uncertainty
   2 Investment is complex and there is moderate to no uncertainty
   3 Investment is simple and there is moderate to no uncertainty

5. The investment's promotion of more flexible capacity, better product quality and improved productivity is essential. Select the most appropriate statement regarding the investment opportunity's impact on the above.
   1 There is very little improvement in the long-term
   2 The investment makes marginal improvements
   3 The investment makes significant long-term improvements

6. Discounted cash flow techniques indicate an investment's long-term profitablity and are used to evaluate the monentary attributes of an investment. Calculate the after-tax present worth of the proposed PMS and choose one of the following.
   1 The present worth is greater than or equal zero
   2 The present worth is less than zero

4.4 System Selection Guide

A graphical selection method to select the optimal manufacturing system was developed by Rice [12] (presented in Figure 8). The vertical axis denotes net production requirements measured in parts per hour, while the horizontal axis represents system flexibility to machine a number of different parts. According to this guideline, it is possible to have a situation which no practical solution exists.

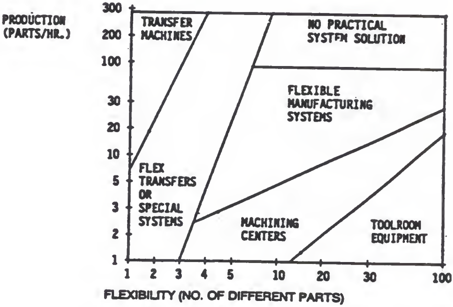

Figure 8: System Selection Guide (12, p. 2)

Toolroom equipment refers to the most basic machine tools found in industries; 1. drill press, 2. lathe, 3. shaper etc.

Machining centers are punched tape or computer controlled machines, often with multiple axis capability and rapid tool changeover.

A flexible manufacturing system here is an automated production system for the manufacture of families of work pieces at mid volume output rates. The system consists of a number of CNC machine tools tied together by a work piece handling system controlled by a host computer.

Flexible transfers or special systems consist of shuttles, in-line transfer and pallet transfer machines. They are arranged to minimize cost and allow adequate flexibility. The use of multiple spindle machines, indexers and various modules are prevalent.

Transfer machines are also called dedicated transfer machines. They are designed to accomodate one or two parts with a very high production volume and production rate.

5. PROPOSED METHOD

In order to determine a suitable manufacturing system for an organization, top management people have a variety of choices as described in the previous chapter. Most of those methods appear to be overly designed for today's industrial application because the majority of these methods depend heavily on complex mathematical modeling, and expert systems where difficult answers were developed. Other methods appear simpler and more useful because multi-criteria decision making techniques were used. Overall, all of them did not go into the most basic elements or components of today's manufacturing industry which were believed to be the determining factors for making automation decisions. The basic components of a manufacturing factory include long term system cost, manning level, set up time, work in process and burden rate.

For the purpose of discussion and pointing out the importance of considering the above basic components, a method for selecting a manufacturing system was developed based on these components.

Basically, a hypothetical manufacturing situation was defined under the proposed method of analysis. A simple cubical product was to be made under the hypothetical situation.

Three popular manufacturing systems: job shop, manufacturing center and cellular manufacturing were choosen to make this product.

Having established all these basic elements; individual system cost, time to produce a batch of the product and work-in-process; they were combined to generate a decision as to which of the three manufacturing systems is the most suitable one to make the product.

This hypothetical situation was choosen because its product has a descrete form. Such environments often have the problem of high capital cost, high manning level, high setup time, considerable work-in-process, long waiting time and expensive shop floor space. The hypothetical situation could be amplified to suit the need of a real life metal working shop.

Process industries such as petroleum refineries, potato chip factories or chemical plants were excluded because they did not face the same set of problems mentioned above. This is probably why many petroleum refineries, potato chip or chemical factories could easily survive despite competition from abroad.

5.1 Objectives of this study

The objectives of this study is to design mathematical models and to predict the system costs of three manufacturing systems. Emphasis has been placed in these models to estimate the value of work-in-process for each system. Traditional costing and selection techniques do not take into consideration this important component.

5.2 Hypothetical Situation.

The hypothetical factory is in a metal working industry, producing aluminium cubes at mid volume (1,000 to 5,000 units per batch). A typical aluminium cube is shown in Figure 9. It has a dimension of 4 inches along all sides, with two holes drilled all the way through the center of two faces. One hole has a diameter of 1 inch, and the other hole was smaller at 0.5 inch. Assume that all finished products are within specifications.

The density of aluminium is 168.6 pounds per cubic foot. Thus, this cube would have a volume of 0.037 cubic feet, and a weight of 6.24 pounds.

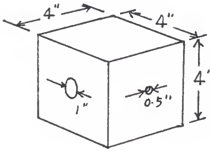

Figure 9: The hypothetical aluminium cube to be made.

The manufacturing process for the cubes are similar under all manufacturing systems. They are stated as follows:

1. Raw material (aluminium casting) were stacked on a pallet placed close to the first operation. One surface was milled off so that a common base could be established and became a reference surface.

2. The cube was placed on the proper fixtures and oriented with the proper mechanism untill all six surfaces were milled according to specifications.

3. The milled metal cube was then placed on a drilling machine where the 1-inch hole was drilled all the way through. It was then reoriented, and the second hole (0.5 inch) was also drilled all the way through.

All finished products were assumed to be within tolerance and placed on a nearby empty pallet and readied for shipment.

There were three different manufacturing systems in this study. They are:

1. The job shop (JS).
2. The machining center, a numerical control machine (NC).
3. The cellular macufacturing system (CM).

Job shop

In a job shop (JS) environment, groups of functionally similar stand-alone machines, for example: a group of drilling machines, and a group of milling machines were placed together at one section of the shop floor. The job shop system required to manufcature the hypothetical part is shown in Figure 10.

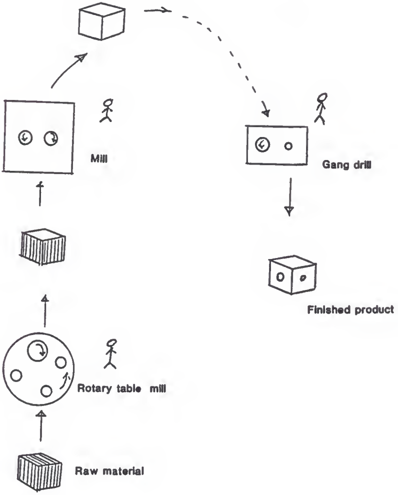

Figure 10: The job shop (JS) manufacturing system required to make the hypothetical part.

The machines were grouped together in this fashion (see Figure 10) so that both operator movement and technical supervision could be minimized. Each worker is assigned to one or several machines in that area and thus become an expert in operating and maintaining that particular group of machines.

The job shop environment required for this hypothetical situation consists of three machines: 1 rotary table mill, 1 conventional mill (with a 2 head cutter) and 1 gang drill. The first task was to feed the raw material into the rotary table milling machine. Two pieces of raw material were clamped onto the first fixtures. When the table rotates, the parts were milled off at the top, thus a reference base was established. The operator running this machine would remove the part from the fixture as it came around, turned it around and reclamped it to the second fixture. The rotary table continued to rotate and thus two sides (top and bottom surfaces) were milled every time a part exited from the rotary table machine.

The operator at the second milling machine grasped a part from the buffer, clamped it on a fixture and let it go through the second milling machine to mill off the remaining four sides of the cube in two passes. This milling machine has a two head cutter (4-inches apart) which allowed any two sides on the cube to be milled simultaneously. After sending the part throught the milling machine two times, a partially finished part emerged and was transported to the drilling area.

The next task was to drill two holes in the cube on a gang drill. Again only one operator was operating the drill. The cube was clamped onto a jig which guided the 1-inch drill. Then it was unclamped, fixed onto the next jig, with the 0.5-inch drill at the adjacent work station. A finished product was thus made.

It must be noted that the two milling machines were located around the same section of the plant, whereas the gang drill was at another section of the plant further away; a characteristic of job shop environment. Thus, parts sat idle when they were transported between stations.

In summary, the basic manufacturing processes for the hypothetical part in a job shop are:

1. On rotary table milling machine.
    - clamp part on first fixture.
    - mill side 1.
    - unclamp part from first fixture.
    - clamp part on second fixture.
    - mill side 2.
    - unclamp from second fixture.

2. On milling machine (with 2 head cutter).
    - clamp part on fixture.
    - mill side 3 and 4.
    - unclamp from fixture.
    - clamp on fixture.
    - mill side 5 and 6.
    - unclamp from fixture.

3. On gang drill.
    - clamp on fixture.
    - drill 1-inch hole.
    - unclamp from fixture, turn it around.
    - clamp on fixture.
    - drill 1/2-inch hole.
    - unclamp and done.

Part ready for shipping.

The machines required for these operations are as follows along with their appropriate costs estimated by Bridgeport Co.:

Rotary mill = $20,000
Mill (with 2 head cutter) = $15,000
Gang drill (2 spindles) = $15,000
Total $50,000

Machining center

In the case of a machining center, a computer controlled (NC) machine was used. It is capable of performing a variety of tasks: milling, drilling according to the programs fed and stored in its memory.

Most numerical control machines have multiple-axes part and tool orientation control capabilities, and thus raw material input could come out as partially finished or finished parts. Advanced machining centers could have automatic tool changing capability. Due to these flexibilities, a machining center could easily function as the nucleus of a highly automated manufacturing system. A simplified drawing of the machining center required to make the hypothetical product is shown in Figure 11. It has a vertically positioned mill cutter.

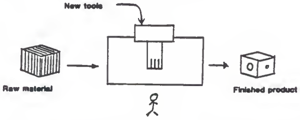

Figure 11: The machining center, a Numerical Control (NC) machine required to make the hypothetical part.

In the case of a NC machine, incoming raw materials were placed on a pallet. The NC machine operator pre-loaded the part program and make the necessary machine setup. The NC machine also has a workholder (see Figure 12) which clamped a part from two sides, and thus allowing more surfaces to be machined.

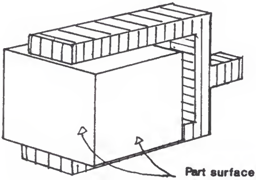

Figure 12: Workholder in NC machine.

The operator clamped the aluminium casting on the machine, hit the "start" button and let the machine positioned itself to mill off one side (established the base). After this operation, the workholder would index once by rotating 90 degrees horizontally, exposing another side of the part. The mill would position accordingly, milled off the exposing surface. Once this was done, the workholder would index again by rotating 90 degrees horizontally and exposing the third surface to be milled. The mill positioned itself and did the cutting. Thus three surfaces were milled.

After these operations, the operator unclamped the part, turned it around, reclamped and started the milling process again. During these processes, intervention by the operator was kept to a minimum. Upon completion of these milling processes, the automated tool changer replaced the milling cutter with a 1-inch diameter drill bit. The part was sitting idle during this changeover.

When the new setup is completed, the 1-inch drill positioned itself to the center of one side of the cube, automatically fed the drill all the way through according to pre-set cutting speed and feed rate. The drill bit went through, then rapid fed itself back to the original position. Meanwhile the tool chnager brought in a 1/2-inch drill bit, and put it in the chuck in place of the 1-inch drill. The workholder also indexed the part by rotating 90 degrees horizontally, and allowed the 1/2-inch drill to reposition, drill all the way through like before. The drill bit then returned to its original position and the original milling cutter was mounted. Thus, a finished aluminium cube was obtained as the cube went through the NC machine.

These basic manufacturing processes can be summarized as on the follow page:

1. In the NC machine.

- clamp part on workholder.
- mill side 1.
- workholder index by rotating 90 degrees horizontally.
- mill side 2.
- workholder index by rotating 90 degrees horizontally.
- mill side 3.
- unclamp part from workholder.
- turn and reclamp part.
- mill side 4.
- workholder index by rotating 90 degrees horizontally.
- mill side 5.
- workholder index by rotating 90 degrees horizontally.
- mill side 6.
- tool change-over from milling cutter to 1-inch drill bit.
- drill 1-inch hole.
- drill returned
- tool change-over (from 1-inch drill to 0.5-inch drill).
- workholder rotate 90 degrees horizontally.
- drill 0.5-inch hole.
- drill returned.
- unclamp and completed.
- tool change over, back to original milling cutter.

part ready for shipment.

The cost of a NC machine with such capabilities, tools and installation were estimated by Bridgeport Co. to be:

Cost of NC machine =	$150,000
Tools, installation =	$ 2,600
Total	$152,600

Cellular manufacturing

Another manufacturing system discussed in this study is the cellular manufacturing system. It consists of a group of manually or computer controlled machines which when taken together are capable of producing a finished product. This manufacturing system is based on the concept of Group Technology (GT) where physically similar parts are grouped together and a partially finished or finished part was made as it go through the manufacturing cell.

A U-shape manufacturing cell was recommended for producing the cube (see Figure 13).

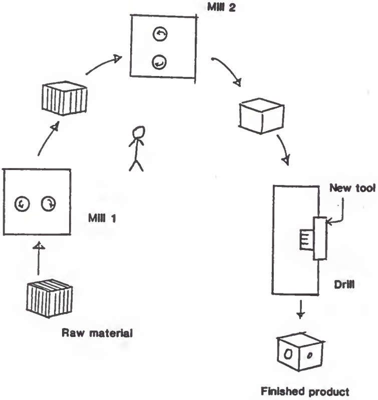

Figure 13: The U-shape cellular manufacturing (CM) system required to make the hypothetical part.

Three machines were required in this cell to make the cube. They consist of two mills, and a drill. Each milling machine has a two-head cutter (4-inches apart) so that any two sides of the cube could be machined at the same time. The drill has only one single spindle but it has an automatic tool-change capability.

The operator running the first milling machine clamped an aluminium casting onto the fixture, release the cutter and allowed two surfaces to be milled. This partially finished part was then moved to a second milling machine where the remaining four sides were milled. Two of these sides were milled each time the cutter went through the part. An operator was necessary to unclamp, reclamp the part every time. These operations allowed all six sides to be milled.

The partially finished part was transferred to the nearby drill immediately. No part was left in a buffer. The operator clamped the part onto a preset jig and allowed the automated feed to drill a 1-inch diameter hole. An automated tool changer replaced the 1-inch drill with a 1/2-inch drill. Meanwhile the operator unclamped, turned the cube 90 degrees horizontally, reclamped the cube and started to feed the drill through the part again. The manufacturing processes in the manufacturing cell can be summarized as follows:

1. On the first milling machine (2 head cutter).
    - clamp part.
    - mill side 1 and 2.
    - unclamp part.

2. On the second milling machine (2 head cutter).
    - clamp part.
    - mill side 3 and 4.
    - unclamp part and rotate.
    - clamp part
    - mill side 5 and 6.
    - unclamp part.

3. On the drill.
    - clamp part.
    - drill 1-inch hole.
    - unclamp, turn part.
      (tool changed to 1/2-inch drill at the same time)
    - clamp part.
    - drill 1/2-inch hole.
    - unclamp, completed.
      (tool change to 1-inch drill at the same time).

An estimated costs for these machines were made by the Bridgeport Co. to be as follows:

Cost of each milling machine (2 head cutter)	= $15,000
	x 2
	$30,000
Drill with automatic tool change	= $25,000
Tools	= $ 600
Total	$55,600

To this point, a product and its hypothetical manufacturing environments have been defined. Three manufacturing systems; job shop, machining center and cellular manufacturing, have been identified.

Other manufacturing assumptions such as the machine cutting speed, feed rate, length of workpiece to be cut, processing time, time required for tool change and indexing will be discussed in the following section. A system-cost model and cost estimation scheme will be developed later, followed by an analysis of the merits of all three manufacturing systems. Finally a conclusion will be made to determine which is the best system for manufacturing this part.

The processing time for various machines were determined based on their appropriate cutting speeds and feed rates found in the Production Process Course Manual [13] and the Materials and Processing in Manufacturing [14].

The cutting speeds and feed rates are as follows:

	Cutting speed (V) in Surface ft/min	Feed rate (f)
milling with carbide tool	800	0.010 ipt
drilling with HSS tool	200	1/2-inch dia 0.007 ipr 1-inch dia 0.015 ipr

Many text books and lab manuals have approximated the RPM (revolutions per minute) of cutters to be as follows:

1. number per revolution of cutter (N) = 4V/D
   where V = cutting speed in SFM
   D = diameter of tool in inches

2. feed (F) = fnN for milling
   (F) = fN for drilling
   where f = feed rate in inches per tooth (ipt) or inches per revolution (ipr).
   n = number of teeth on cutter
   N = number of revolution per minute, rpm

3. cutting time (CT) = L/F units
   where L = length of workpiece path in inches
   F = feed in inches/minute

A) Thus for milling aluminum with a carbide tool (6-inches in diameter):

$$N = \frac{4V}{D} = \frac{4(800)}{6} = 533 \text{ rpm}$$

using f = 0.010 ipt

Assuming that the carbide tool has 16 teeth, and allows 8 inches over-travel, the length of work piece to be milled, is 4 + 8 = 12 inches.

$$F = fnN = 0.010 \times 16 \times 533 = 85.3 \text{ in/min}$$

$$CT = \frac{12 \text{ in} \times 60 \text{ sec/min}}{85.3 \text{ in/min}} = 8.44 \text{ sec}$$

B) For milling aluminum with a two head cutter (carbide material), each cutter 10 inches in diameter:

$$N = \frac{4V}{D} = \frac{4(800)}{10} = 320 \text{ rpm}$$

Using f = 0.010 ipt

By assuming that the carbide tool has 10 teeth, and allowed 10 inches over-travel, the length of work piece to be milled, is 4 + 10 = 14 inches.

$$F = fnN = 0.010 \times 10 \times 320 = 32 \text{ in/min}$$

$$CT = \frac{14 \text{ in} \times 60 \text{ sec/min}}{32 \text{ in/min}} = 26.25 \text{ sec}$$

C) For drilling 1/2-inch diameter HSS drill bit,

$$N = \frac{4V}{D} = \frac{4(200)}{1/2} = 1{,}600 \text{ rpm}$$

Using f = 0.007 ipt

$$F = fN = 0.007 \times 1{,}600 = 11.2 \text{ in/min}$$

Assuming that drill bit was 1.5 inches above the workpiece before drilling and an overtravell of 0.5 inch (for the drill bit to go all the way through). Thus the drill actually travelled

1.5 + 4 + 0.5 = 6 inches when drilling.

$$CT = \frac{6 \text{ in} \times 60 \text{ sec/min}}{11.2 \text{ in/min}} = 32.14 \text{ sec}$$

D) For drilling 1 inch diameter with a HSS drill bit,

$$N = \frac{4V}{D} = \frac{4(200)}{1} = 800 \text{ rpm}$$

Using f = 0.015 ipt

$$F = fN = 0.015 \times 800 = 12 \text{ in/min}$$

Again by assuming that drill bit was 1.5 inches above workpiece before drilling and an overtravell of 0.5 inch (for the drill bit to go all the way through). Thus drill actually travelled

1.5 + 4 + 0.5 = 6 inches when drilling.

$$CT = \frac{6 \text{ in} \times 60 \text{ sec/min}}{12 \text{ in/min}} = 30 \text{ sec}$$

In summary:

Task	Processing time in seconds.
Milling with a 6-inches diameter carbide tool	8.44 sec
Milling with a 10-inches diameter carbide tool (2-head cutter)	26.25 sec
Drilling with a 1/2-inch diameter HSS drill bit	32.14 sec
Drilling with a 1-inch diameter HSS drill bit	30.00 sec

These processing times were combined with the appropriate operator time as shown in the following pages.

In a job shop environment:

Task	Processing time (sec)	Operator time (sec)
1. On rotary table milling machine.		
- unload part from pallet.		8.00
- clamp part on first fixture.		8.00
- mill side 1.	8.44	
- unclamp part from first fixture.		9.00
- clamp part on second fixture.		8.00
- mill side 2.	8.44	
- unclamp from second fixture.		9.00
- load part into pallet		8.00
	16.88	50.00
2. On milling machine (with 2 head cutter)		
- unload part from pallet.		8.00
- clamp part on fixture.		15.00
- mill side 3 and 4.	26.25	
- unclamp from fixture.		17.00
- clamp on fixture.		15.00
- mill side 5 and 6.	26.25	
- unclamp from fixture.		17.00
- load part into pallet		8.00
	52.50	80.00
3. On gang drill.		
- unload part from pallet.		8.00
- clamp on fixture.		18.00
- drill 1-inch hole.	30.00	
- unclamp from fixture, turn it around.		20.00
- clamp on fixture.		18.00
- drill 1/2-inch hole.	32.14	
- unclamp and done.		20.00
- load part into pallet		8.00
	62.14	92.00
Total time	131.52	222.00

In a machining center:

Task	Processing time (sec)	Operator time (sec)
1. In NC machine.		
- clamp part on workholder.		25.00
- mill side 1.	8.44	
- workholder index by rotating 90 degrees horizontally.		10.00
- mill side 2.	8.44	
- workholder index by rotating 90 degrees horizontally.		10.00
- mill side 3.	8.44	
- unclamp part from workholder.		20.00
- turn and reclamp part.		45.00
- mill side 4.	8.44	
- workholder index by rotating 90 degrees horizontally.		10.00
- mill side 5.	8.44	
- workholder index by rotating 90 degrees horizontally.		10.00
- mill side 6.	8.44	
- unclamp part from workholder.		20.00
- tool change-over (from mill to 1-inch drill). Clamp part on workholder.		23.00
- drill 1-inch hole.	30.00	
- drill returned		5.00
- tool change-over (from 1-inch drill to 0.5-inch drill), workholder rotated 90 degrees horizontally.		10.00
- drill 0.5-inch hole.	32.14	
- drill returned.		5.00
- unclamp and done.		20.00
- tool change back to milling cutter.		30.00
Total time	112.78	243.00

In a cellular manufacturing environment:

Task	Processing time (sec)	Operator time (sec)
1. On first milling machine (2 head cutter).		
- clamp part.		20.00
- mill side 1 and 2.	26.25	
- unclamp part.		22.00
	26.25	42.00
2. On second milling machine (2 head cutter).		
- clamp part.		20.00
- mill side 3 and 4.	26.25	
- unclamp part.		22.00
- clamped part.		20.00
- mill side 5 and 6.	26.25	
- unclamp part.		22.00
	52.50	84.00
3. On drill.		
- clamp part.		18.00
- drill 1-inch hole.	30.00	
- unclamp and turn part. (tool change to 1/2-inch drill at the same time)		20.00
- clamp part.		18.00
- drill 1/2-inch hole.	32.14	
- unclamp part and done. (tool change back to 1-inch drill at the same time)		20.00
	62.14	76.00
Total time	140.89	202.00

5.3 System Cost

Cost is the sacrifice of resources. It is also the price one needs to pay in order to acquire something or to accomplish something. The same theory can be applied to a manufacturing process when one wants to make a product. In order for someone to make a product, one needs to sacrifice many resources and pay a price for each of those items. Examples of these resources are: raw material, skills from a laborer, energy (electrical, heat or mechanical), and machines among many others. Each of these resources has a price associated with it and by carefully classifying and quantifying them, one can estimate the cost of a product at the end of the manufacturing process.

The cost accounting procedure by E. Deakin and M. Maher [15] said that the total cost of a product comes from three categories, namely:

1. Direct material cost.
2. Direct labor cost.
3. Manufacturing overhead or burden cost.

Direct material cost can be called raw material cost. It is the material that one is processed and which becomes the finished product. The raw material can be manufactured in-house or can be purchased from outside vendors. In any event, the cost of obtaining the material will contribute to the direct material cost. In this study, the raw material is small aluminium castings purchased from an outside vendor.

Direct labor cost is the cost of people who work directly with the material and are responsible for transforming it into the finished product.

Manufacturing overhead or burden cost refers to all other costs of transforming a piece of material into its final form. E. Deakin and M. Maher [15] pointed out that this cost alone comes from three categories. They are:

i. Indirect labor -- This is the labor that do not work directly with the raw material, but yet they are necessary to help transforming the material to its final form. Examples of this are: supervisors, maintenance workers, inventory storekeepers, janitors and others.

ii. Indirect material -- This refers to materials which are necessary to produce a product but do not become part of the finished product. Examples of this are: machinery lubricant, polishing and cleaning material, spare parts etc.

iii. Other manufacturing cost -- This includes any other costs which go into making a product but do not become part of the final product. Examples of this are: machinery and plant depreciation, insurance for workers and factory, enery (heat, electrical etc) and others.

Thus, it can be seen that the cost of a manufactured product comes from a wide variety of areas. In this study, the emphasis is on the cost of manufacturing a batch of products. We shall examine separately the costs related to three different manufacturing systems when producing a batch of aluminium parts. Because the entire system has been taken into account, the total cost shall be referred to as the system cost (S). The system cost is therefore a summation of a wide variety of costs. It can be expressed as follows:

System cost (S) = Direct material cost + Direct labor cost +
Manufacturing overhead (or burden cost)

The direct material cost will not be included in the system cost equation because this cost is the same for the three systems. The resultant of this cost is also the same for all systems.

Breaking the above relationship into its basic elements, we obtain

System cost (S) = (capital rate + direct labor rate +
burdon cost + power and utility rate) x
time per batch

$$S = (C_C + C_L + C_B + X_{PU} R) \times T_B$$

The cost of capital or machinery depends on the individual manufacturing system (cost stated in section 5.1) and they were obtained from Bridgeport Machinery Company. Each machine is expected to last for 10 years. Assuming that the plant is operating a single shift at 2,000 hours per year and each machine is working at 85 percent machine utilization capacity. Therefore the capital cost can be defined as:

$$C_C = \frac{\text{Capital cost or equipment cost}}{2{,}000 \text{ hrs/yr} \times 10 \text{ yrs} \times 0.85}$$

$$= \frac{\text{Capital cost or equipment cost}}{17{,}000 \text{ hrs}}$$

The cost of direct labor, (C_L) is assumed to be at $8 per hour; a rate for small town, non-union work environment.

The burden rate (C_B), which consists of all indirect labor cost and indirect material cost and is assumed to be at 100% of the original direct labor rate. Thus C_B = $8/hr.

Power and utility costs are based on the kilowatt (kw) rating (X_{PU}) established by the machine manufacturer, and the price (R) of electricity in $ per kwh. The price used is 1 kwh = $0.0517 based on the 1986 statistical average [16].

The time required to produce a batch of products (T_B) is based on the setup time, processing time, operator time and the number of parts in a batch. The time per batch can be expressed as:

$$T_B = \text{setup time} + (\text{processing time} + \text{operator time}) \times \text{number of parts}$$

$$T_B = T_{SU} + (T_{PR} + T_{OP})N$$

Thus the cost equation of any manufacturing system can be expressed as:

$$S = (C_C + C_L + C_B + X_{PU}R) \times (T_{SU} + (T_{PR} + T_{OP})N)$$

As in any manufacturing environment, raw materials do not go into the production area and emerge spontaneously as a finished product. There are usually parts stored in a manufacturing system in different forms. It could be in a form of a piece of partially finished product waiting to be transported to the next work station or waiting in a queue to be processed or even a part waiting while the machine changes tools. For instance in the case of a job shop, there could be more than one part, maybe a thousand parts simultaneously waiting to be worked on. In the case of a machining center, usually a single part is idle while the machine changes tools. All of these parts are called work-in-process and this cost should not be overlooked as well. It should be added to the original system cost equation as in the following.

$$S = (C_C + C_L + C_B + X_{PU} R) \times (T_{SU} + (T_{PR} + T_{OP})N) + X_{WIP}$$

Typically, the cost of work-in-process measures the basic material cost and the value added to the material while they exist in the production system. Thus the cost of work-in-process (X_{WIP}) is a function of the material cost, burden cost and their inventory carrying rate. To illustrate the significance of work-in-process, consider the work-in-process model below (see Figure 14).

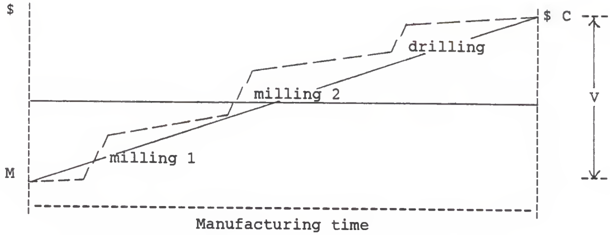

Figure 14: Work-in-process model (17, p. 270)

M = cost of raw material.
C = cost of finished product.
V = value added to material during transformation (C - M).

Ideally the value added can be shown as the non-uniform dotted line in Figure 14 above, due to the manufacturing process cost and overhead cost. As for our calculation, we shall assume that labor and factory expenses are applied at a constant rate, thus a straight line is obtained (shown as the solid line in Figure 14). The value added to a part (V) is derived from the manufacturing, labor and burden cost during that period and it can be calculated from

$$V = \sum_{\text{machines}} (C_C + C_L + C_B + C_{PU} R) T_B$$

The horizontal line mid-way between the material cost (M) and the finished product cost (C) in Figure 14 shows the average value added. The material cost will be added into this average value added for computing the cost of WIP.

$$\text{WIP cost} = \left(M + \frac{V}{2}\right)LK$$

where M = raw material cost for a batch. M = mN,
m = cost per part and N = batch size.
V = average value added for a batch.
L = Manufacturing cycle time or lead time.
K = inventory carrying rate (assume K = \$0.30/\$yr).
it means that the inventory carrying cost is \$0.30 for every dollar worth of inventory carried per year.

Thus a more complete form of the system cost equation is

$$S = (C_C + C_L + C_B + X_{PU} R) \times (T_{SU} + (T_{PR} + T_{OP})N) + \left(M + \frac{V}{2}\right)LK$$

or

$$S = (C_C + C_L + C_B + X_{PU} R) \times \{T_{SU} + (T_{PR} + T_{OP})N\} + \left(M + \frac{\sum_{\text{machine}} (C_C + C_L + C_B + C_{PU} R) \times (T_{SU} + (T_{PR} + T_{OP})N)}{2}\right)LK$$

With this equations, it is now possible to estimate the system cost for the three manufacturing systems: job shop, machining center and cellular manufacturing. Several variations of these three systems will be examined as well. They are:

1. conventional job shop.
2. variations in the job shop (case with different queue time).
3. machining center.
4. cellular manufacturing with 1 operator.
5. cellular manufacturing with 2 operators.

5.3.1 Job shop

In a job shop, a batch of work pieces is completely transformed on one machine before it is moved to the next machine. Work pieces do not flow continuously in the production line, and machines are functioning independently of each other. The manufacturing cost in the job shop is therefore confined to the processing of a batch of products on one machine at a time. The system cost equation for the job shop needed to be modified slightly to reflect the cost related to each machine separately rather than all machines combined. The system cost of a job shop becomes

$$S_{JS} = \sum_{i=1}^{3} (C_{Ci} + C_{Li} + C_{Bi} + X_{PUi} R) \times \{T_{SUi} + (T_{PRi} + T_{OPi})N\} + \left(M + \frac{\sum_{\text{all machines}} (C_{Ci} + C_{Li} + C_{Bi} + C_{PUi} R)T_{Bi}}{2}\right)LK$$

where $T_{Bi} = T_{SUi} + (T_{PRi} + T_{OPi})N$

C_{Ci} = capital cost tied up with machine i.

C_{Li} = labor cost tied up with machine i.

C_{Bi} = burden cost tied up with machine i.

X_{PUi} = power rating for machine i.

T_{SUi} = setup time for machine i.

T_{PRi} = processing time for material on machine i.

T_{OPi} = operator time tied up in machine i.

N = batch size

machine 1 = rotary table milling machine.

machine 2 = milling machine with 2 head cutter.

machine 3 = gang drill.

Job shop

machine number	R. table 1	Milling 2	G. drill 3
Machine cost	$20,000	$15,000	$15,000
Machine life	10 years	10 years	10 years
Machine utilization	85%	85%	85%
Working hrs/yr	2,000	2,000	2,000
Direct labor (C_L)	$8/hr	$8/hr	$8/hr
Burden cost (C_B)		100% of direct labor	
Machine power rating	0.15 kw	0.15 kw	0.15 kw
Cost of electricity	$0.0517/kwh	$0.0517/kwh	$0.0517/kwh
Setup time	1,500 sec	1,800 sec	600 sec
Processing time	16.88 sec	52.50 sec	62.14 sec
Operator time	50.00 sec	80.00 sec	92.00 sec

The system cost of a job shop (S_{JS}) is

$$S_{JS} = S_{R.\ table} + S_{Mill} + S_{G.\ drill} + X_{WIP}$$

Rotary table milling machine

This is the first machine in the job shop.

$$C_{C1} = \frac{\text{Total capital cost}}{\text{Machine life in hours.}} = \frac{\$20{,}000}{17{,}000 \text{ hrs}} = \$1.176/\text{hr}$$

C_{B1} = All indirect labor and material costs
= 100% direct labor
= 100% x $8/hr = $8/hr

$$T_{B1} = T_{SU1} + N(T_{PR1} + T_{OP1})$$

$$T_{B1} = \frac{1{,}500 + N(16.88 + 50.00) \text{ sec}}{3{,}600 \text{ sec/hr}} = (0.417 + 0.0186N) \text{ hr}$$

$$S_{R.\ table} = \$(1.176 + 8 + 8 + 0.0517x0.15)/\text{hr} \times T_{B1} \text{ hr} = \$17.184T_{B1}$$

milling machine

This is the second machine in the job shop.

$$C_{C2} = \frac{\text{Total capital cost}}{\text{Machine life in hours.}} = \frac{\$15{,}000}{17{,}000 \text{ hrs}} = \$0.882/\text{hr}$$

C_{B2} = All indirect labor and material costs
= 100% direct labor
= 100% x \$8/hr = \$8/hr

$$T_{B2} = T_{SU2} + N(T_{PR2} + T_{OP2})$$

$$T_{B2} = \frac{1{,}800 + N(52.50 + 80.00) \text{ sec}}{3{,}600 \text{ sec/hr}} = (0.50 + 0.0368N) \text{ hr}$$

Thus $S_{mill} = \$(0.882 + 8 + 8 + 0.0517 \text{x} 0.15)/\text{hr} \text{ x } T_{B2} \text{ hr}$

$S_{mill} = \$16.890T_{B2}$

Gang drill

This is the third machine in the job shop.

$$C_{C3} = \frac{\text{Total capital cost}}{\text{Machine life in hours.}} = \frac{\$15{,}000}{17{,}000\ \text{hrs}} = \$0.882/\text{hr}$$

$$C_{B3} = \text{All indirect labor and material cost}$$
$$= 100\%\ \text{direct labor}$$
$$= 100\% \times \$8/\text{hr} = \$8/\text{hr}$$

$$T_{B3} = T_{SU3} + N(T_{PR3} + T_{OP3})$$

$$T_{B3} = \frac{600 + N(62.14 + 92.00)\ \text{sec}}{3{,}600\ \text{sec/hr}} = (0.167 + 0.0428N)\ \text{hr}$$

Thus $S_{G.\ drill} = \$(0.882 + 8 + 8 + 0.0517\text{x}0.15)/\text{hr} \times T_{B3}\ \text{hr}$

$$S_{G.\ drill} = \$16.890T_{B3}$$

In summary

machine #	R. table 1	Mill 2	G. drill 3
C_{Ci}	\$1.176/hr	\$0.882/hr	\$0.882/hr
C_{Li}	\$8/hr	\$8/hr	\$8/hr
C_{Bi}	\$8/hr	\$8/hr	\$8/hr
C_{PUi}	\$0.007	\$0.007	\$0.007
T_{Bi}	(0.417+0.0186N)hr	(0.5+0.0368N)hr	(0.167+0.0428N)hr
T_{Si}	$\$17.184T_B$	$16.890T_B$	$16.890T_B$

The system cost of a job shop

$$S_{JS} = S_{R.\ table} + S_{Mill} + S_{G.\ drill} + X_{WIP}$$

becomes

$$S_{JS} = 17.184T_{B1} + 16.890T_{B2} + 16.890T_{B3} + X_{WIP}$$

Substitute values of T_{B1}, T_{B2} and T_{B3} into S_{JS}

$$S_{JS} = 17.184 \times (0.417 + 0.0186N)\text{hr} + 16.890 \times (0.500 + 0.0368N)\text{hr} + 16.890 \times (0.167 + 0.0428N)\text{hr} + X_{WIP}$$

$$S_{JS} = \$(7.165 + 0.320N + 8.445 + 0.621N + 2.82 + 0.723N) + X_{WIP}$$

$$S_{JS} = \$(18.43 + 1.664N + X_{WIP})$$

To calculate the cost of work-in-process (X_{WIP})

$$X_{WIP} = (\text{avg WIP value}) \times (\text{carrying rate}) \times (\text{lead time})$$

$$X_{WIP} = V_{WIP} \times 0.30 \times L$$

Average WIP value (V_{WIP})

$$V_{WIP} = (M + \frac{V}{2})$$

where M = cost of aluminium casting
= 6.24 lb/part x N parts x \$3.50/lb [18]
= \$21.84N
V = value added to material
= manufacturing cost rate x T_B

$$V = \sum_{\substack{\text{all} \\ \text{machines}}} (C_C + C_L + C_B + X_{PU} R) T_B$$

$$= S_{R.\ table} + S_{Mill} + S_{Drill}$$

$$= 17.184 T_{B1} + 16.89 T_{B2} + 16.89 T_{B3}$$

$$\begin{aligned} V = {} & 17.184 \times (0.417 + 0.0186N)\text{hr} + \\ & 16.890 \times (0.500 + 0.0368N)\text{hr} + \\ & 16.890 \times (0.167 + 0.0428N)\text{hr} \end{aligned}$$

$$V = \$(18.43 + 1.664N)$$

Substitute the V value into V_{WIP} equation.

$$V_{WIP} = \$(21.84N + \frac{18.43 + 1.664N}{2})$$

Lead time (L)

$$L = \frac{\sum \text{all cycle time}}{0.05} = \frac{(131.52 + 222.0)N}{0.05} = 7070.4N \text{ sec}$$

See section 5.3.2 (page 59) for reference to the above formula.

Cost of WIP (X_{WIP})

$$X_{WIP} = \left(21.84N + \frac{18.43 + 1.664N}{2}\right) \times 0.3 \times \frac{7070.4N \text{ sec}}{3{,}600 \text{ sec/hr}}$$

$$= \$(5.429N + 13.358N^2)$$

Therefore the system cost of a job shop is:

$$S_{JS} = 18.43 + 1.664N + X_{WIP}$$

$$S_{JS} = 18.43 + 1.664N + (5.429N + 13.358N^2)$$

$$S_{JS} = \$(18.43 + 7.093N + 13.358N^2)$$

Since the cycle time is assumed to be 5% of the lead time (L), the system cost S_{JS} will be symbolized as $S_{js5\%L}$.

5.3.2 Variations in job shop

The greatest portion of lead time (up to 90% and more) in a job shop usually comes from queue time [19]. When queue time is reduced, parts will be processed more rapidly and work-in-process will be reduced. In the previous section, 95 percent of the lead time has been used as parts queue time, only 5 percent of the remaining lead time served as useful production time or cycle time. In this section, total cycle time has been set at various levels (10%, 90% and 100%) of lead time (L) where

$$L = \frac{\sum \text{all cycle time}}{\%\ \text{of}\ L} = \frac{353.52\ \text{sec}}{\%\ \text{of}\ L}$$

New L values have to be computed and substituted in the X_{WIP} equation.

where

$$X_{WIP} = V_{WIP} \times 0.30 \times L$$

We obtained:

% of lead time (L)	Lead time (L)	X_{WIP}
10	3535.20 sec	$2.715N + 6.679N^2$
90	392.80 sec	$0.302N + 0.742N^2$
100	353.52 sec	$0.271N + 0.668N^2$

Substitute these new X_{WIP} values in the system cost equations. The following results were obtained:

% of lead time (L)	S_{JS}
10	$18.43 + 4.379N + 6.679N^2$
90	$18.43 + 1.966N + 0.742N^2$
100	$18.43 + 1.935N + 0.668N^2$

An idealized job shop is obtained when cycle time is equal to 100 percent of the lead time. This idealized case is only achievible in theory.

5.3.3 Machining center

The only machine used in the machining center is a Numerical Control (NC) machine. Parts are transformed from castings to the finishing form in the NC machine one piece at a time. There is one major setup for this machine and parts normally only have to wait for tool change. Thus, the entire NC machine investment is tied up for each batch of products.

The system cost equation for the machining center is

$$S_{NC} = (C_C + C_L + C_B + Y_{PU}\,R) \times \{T_{SU} + (T_{PR} + T_{OP})N\} + \left(M + \frac{(C_C + C_L + C_B + Y_{PU}\,R)T_B}{2}\right)LK$$

	NC machine
Machine cost	$152,600
Machine life	10 years
Machine utilization	85%
Working hrs/yr	2,000
Direct labor (C_L)	$8/hr
Burden cost (C_B)	100 % of direct labor
Machine power rating	2 kw
Cost of electricity	$0.0517/kwh
Setup time (T_{SU})	1,800 sec
Processing time (T_{PR})	112.78 sec
Operator time (T_{OP})	243.00 sec

$$C_C = \frac{\text{Total capital cost}}{\text{Machine life in hours.}} = \frac{\$152,600}{17,000\text{ hrs}} = \$8.98/\text{hr}$$

C_B = All indirect labor and material cost
$= 100\%$ direct labor
$= 100\% \times \$8/\text{hr} = \$8/\text{hr}$

Thus $S_{NC} = (8.98 + 8 + 8 + 0.0517 \times 2.00)T_B + Y_{WIP}$
$= 25.083T_B + Y_{WIP}$

where

$$T_B = T_{SU} + N(T_{PR} + T_{OP})$$

$$T_B = \frac{1,800 + N(112.78 + 243.00)\text{ sec}}{3,600\text{ sec/hr}} = (0.50 + 0.0988N)\text{hr}$$

or

$$S_{NC} = \$25.083/\text{hr} \times (0.50 + 0.0988N)\text{hr} + Y_{WIP}$$

$$S_{NC} = \$(12.541 + 2.478N + Y_{WIP})$$

To calculate the cost of work-in-process (Y_{WIP}) for the machining center.

$$Y_{WIP} = (\text{avg WIP value}) \times (\text{carrying rate}) \times (\text{lead time})$$

$$Y_{WIP} = V_{WIP} \times 0.30 \times L$$

$$V_{WIP} = (M + \frac{V}{2})$$

where M = cost of aluminium casting
$= 6.24\text{ lb/part} \times N\text{ parts} \times \$3.50/\text{lb}$ [18]
$= \$21.84N$
V = value added to material
= manufacturing cost $\times T_B$

$$V = (C_C + C_L + C_B + Y_{PU} R)T_B$$

$$V = \$(8.98 + 8 + 8 + 0.0517 \times 2.00)/\text{hr} \times (0.50 + 0.0988N)\text{hr}$$

$$V = \$(12.541 + 2.478N)$$

Substitute V value into V_{WIP} equation.

$$V_{WIP} = \$\left(21.84N + \frac{12.541 + 2.478N}{2}\right)$$

the lead time (L) is

$$L = \text{number of parts} \times \text{cycle time} = N \times 355.78 \text{ sec}$$
$$L = 355.78N \text{ sec}$$

$$Y_{WIP} = \$\left(21.84N + \frac{12.541 + 2.478N}{2}\right) \times 0.3 \times \frac{355.78N \text{ sec}}{3{,}600 \text{ sec/hr}}$$

$$= \$(0.186N + 0.684N^2)$$

Therefore the system cost of a machining center is:

$$S_{NC} = \$(12.541 + 2.478N + Y_{WIP})$$

$$S_{NC} = \$(12.541 + 2.478N + (0.186N + 0.684N^2)$$

$$S_{NC} = \$(12.541 + 2.664N + 0.684N^2)$$

5.3.4 Cellular Manufacturing with 1 operator

A manufacturing cell is used to process a family of parts which share a major setup and may require some minor setups for different parts in the family. Normally a part progresses from one machine to the next and emerges from the cell as a completely finished product. Ideally each machine has a part to be worked on at anytime, but machine balancing problem may arise when the operator is busy at one machine and can not attend the other machine/s.

In this study, one operator is attending three machines in the manufacturing cell. The capital cost and labor cost will be combined and distributed throughout the time required to produce a batch of product.

The system cost equation is

$$S_{CM1} = \sum_{\substack{\text{all} \\ \text{machines}}} (C_C + C_L + C_B + Z_{PU} R) \times \{T_{SU} + (T_{PR} + T_{OP})N\} + \left(M + \frac{\sum_{\substack{\text{all} \\ \text{machines}}} (C_C + C_L + C_B + Z_{PU} R)T_B}{2}\right)LK$$

	Mill 1	Mill 2	Drill
Machine cost	$15,000	$15,000	$25,600
Machine life	10 years	10 years	10 years
Machine utilization	85%	85%	85%
Working hrs/yr	2,000	2,000	2,000
Direct labor (C_L)	$8/hr	$8/hr	$8/hr
Burden cost (C_B)	100% of direct labor		
Machine power rating	0.15 kw	0.15 kw	2.00 kw
Cost of electricity/kwh	$0.0517	$0.0517	$0.0517

	Mill 1	Mill 2	Drill
Setup time	1,200 sec	1,200 sec	1,200 sec
Processing time	26.25 sec	52.50 sec	62.14 sec
Operator time	42.00 sec	84.00 sec	76.00 sec

$$C_C = \frac{\text{Total capital cost}}{\text{Machine life in hours.}} = \frac{\$55{,}600}{17{,}000 \text{ hrs}} = \$3.27/\text{hr}$$

$$C_B = \text{All indirect labor and material cost}$$
$$= 100\% \text{ direct labor}$$
$$= 100\% \text{ x } \$8/\text{hr} = \$8/\text{hr}$$

Thus $S_{CM1} = (3.27 + 8 + 8 + 0.0517\text{x}2.30)T_B + Z_{WIP}$

$$= 19.389T_B + Z_{WIP}$$

where

$$T_B = T_{SU} + N(T_{PR} + T_{OP}) = T_{SU} + N(T_{cycle})$$

$$T_B = \frac{(3{,}600 + 202N) \text{ sec}}{3{,}600 \text{ sec/hr}} = (1.000 + 0.0561N) \text{ hr}$$

or

$$S_{CM1} = \$19.389/\text{hr x } (1.000 + 0.0561)\text{hr} + Z_{WIP}$$

$$S_{CM1} = \$(19.389 + 1.0877N + Z_{WIP})$$

To calculate the cost of work-in-process (Z_{WIP})

$$Z_{WIP} = (\text{avg WIP value}) \text{ x } (\text{carrying rate}) \text{ x } (\text{lead time})$$

$$Z_{WIP} = V_{WIP} \text{ x } 0.30 \text{ x } L$$

$$V_{WIP} = (M + \frac{V}{2})$$

where M = cost of aluminium casting
= 6.24 lb/part x N parts x \$3.50/lb [18]
= \$21.84N
V = value added to material
= manufacturing cost x T_B

$$V = \sum_{\substack{\text{all} \\ \text{machines}}} (C_C + C_L + C_B + Y_{PU} R) T_B$$

$$V = \$(3.27 + 8 + 8 + 0.0517 \times 2.30)/\text{hr} \times (1 + 0.0561N)\ \text{hrs}$$

$$V = \$(19.389 + 1.0877N)$$

Substitute the V value into V_{WIP} equation.

$$V_{WIP} = \$\left(21.84N + \frac{19.389 + 1.0877N}{2}\right)$$

the cycle time is found from the man-machine chart in Fig 15 (one operator in cell).

The lead time, L is

L = number of parts x cycle time = N x 202.00 sec
L = 202.00N sec

$$Z_{WIP} = \$\left(21.84N + \frac{19.389 + 1.0877N}{2}\right) \times 0.3 \times \frac{202.00N\ \text{sec}}{3{,}600\ \text{sec/hr}}$$

$$= \$(0.163N + 0.377N^2)$$

Therefore the system cost of a manufacturing cell is

$$S_{CM1} = 19.389 + 1.0877N + Z_{WIP}$$

$$S_{CM1} = \$(19.389 + 1.0877N + (0.163N + 0.377N^2))$$

$$S_{CM1} = \$(19.39 + 1.251N + 0.377N^2)$$

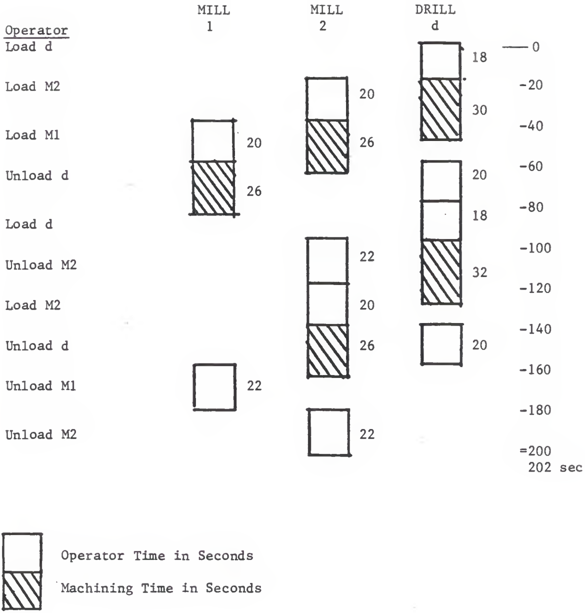

Figure 15: Man-machine chart (one operator in cell)

5.3.5 Cellular Manufacturing with 2 operators

In this case, two operators attend three machines in the manufacturing cell. Each machine operator may be in charge of one or more machines. Idle time for each work has to be kept to minimum. Parts progress in the cell from one machine to the next. The capital cost and labor cost will be combined and distributed throughout the time required to produce a batch of product.

The system cost equation is

$$S_{CM2} = \sum_{\substack{\text{all} \\ \text{machines}}} (C_C + C_L + C_B + Z_{PU} R) \times \{T_{SU} + (T_{PR} + T_{OP})N\} + \left(M + \frac{\sum_{\substack{\text{all} \\ \text{machines}}} (C_C + C_L + C_B + Z_{PU} R)T_B}{2}\right)LK$$

	Mill 1	Mill 2	Drill
Machine cost	\$15,000	\$15,000	\$25,600
Machine life	10 years	10 years	10 years
Machine utilization	85%	85%	85%
Working hrs/yr	2,000	2,000	2,000
Direct labor (C_L)	\$8/hr	\$8/hr	\$8/hr
Burden cost (C_B)	100% of direct labor		
Machine power rating	0.15 kw	0.15 kw	2.00 kw
Cost of electricity/kwh	\$0.0517	\$0.0517	\$0.0517
Setup time	1,200 sec	1,200 sec	1,200 sec
Processing time	26.25 sec	52.50 sec	62.14 sec
Operator time	42.00 sec	84.00 sec	76.00 sec

$$C_C = \frac{\text{Total capital cost}}{\text{Machine life in hours.}} = \frac{\$55,600}{17,000 \text{ hrs}} = \$3.27/\text{hr}$$

C_B = All indirect labor and material costs
= 100% direct labor
= 100% x \$8/hr = \$8/hr

Eventhough the manufacturing cell now has 2 operators, the level of supervision, maintenance or janitorial service would still remain the same as in the case of 1 operator in the cell. Indirect material cost due to greater use of machine lubricant, cleaning fluids is insignificant. Thus burden cost with 2 operators is maintained at 100 percent of \$8 instead of \$16 for the value of 2 operators.

$$S_{CM2} = (3.27 + 16 + 8 + 0.0517x2.30)T_B + Z_{WIP} = 27.389T_B + Z_{WIP}$$

where

$$T_B = T_{SU} + N(T_{PR} + T_{OP}) = T_{SU} + N(T_{cycle})$$

$$T_B = \frac{1{,}800 + N(138.14) \text{ sec}}{3{,}600 \text{ sec/hr}} = (0.50 + 0.0384N) \text{ hr}$$

$$S_{CM2} = \$27.389/hr \text{ x } (0.50 + 0.0384N)hr + Z_{WIP}$$

$$S_{CM2} = \$(13.695 + 1.0517N + Z_{WIP})$$

To calculate the cost of work-in-process (Z_{WIP})

$$Z_{WIP} = (\text{avg WIP value}) \text{ x } (\text{carrying rate}) \text{ x } (\text{lead time})$$

$$Z_{WIP} = V_{WIP} \text{ x } 0.30 \text{ x } L$$

$$V_{WIP} = (M + \frac{V}{2})$$

where M = cost of aluminium casting

$= 6.24\ \mathrm{lb/part} \times N\ \mathrm{parts} \times \$3.50/\mathrm{lb}$ [18]

$= \$21.84N$

V = value added to material

$=$ manufacturing cost $\times\ T_B$

$$V = \sum_{\substack{\text{all} \\ \text{machines}}} (C_C + C_L + C_B + Y_{PU} R) T_B$$

$$V = \$(3.27 + 16 + 8 + 0.0517 \times 2.30)/\mathrm{hr} \times (0.50 + 0.0384N)\mathrm{hr}$$

$$V = \$(13.695 + 1.0517N)$$

Substituting the V value into V_{WIP} equation.

$$V_{WIP} = \$(21.84N + \frac{13.695 + 1.0517N}{2})$$

the cycle time is found from the man-machine chart in Fig 16 (two operators in a cell). The lead time, L is

L = number of parts x cycle time = $N \times 138.14$ sec

$L = 138.14N$ sec

$$Z_{WIP} = (21.84N + \frac{13.695 + 1.0517N}{2}) \times 0.3 \times \frac{138.14N\ \mathrm{sec}}{3{,}600\ \mathrm{sec/hr}}$$

$$= \$(0.0788N + 0.257N^2)$$

Therefore the system cost of a manufacturing cell is

$$S_{CM2} = 13.695 + 1.0517N + Z_{WIP}$$

$$S_{CM2} = 13.695 + 1.0517N + (0.0788N + 0.257N^2)$$

$$S_{CM2} = 13.695 + 1.1305N + 0.257N^2$$

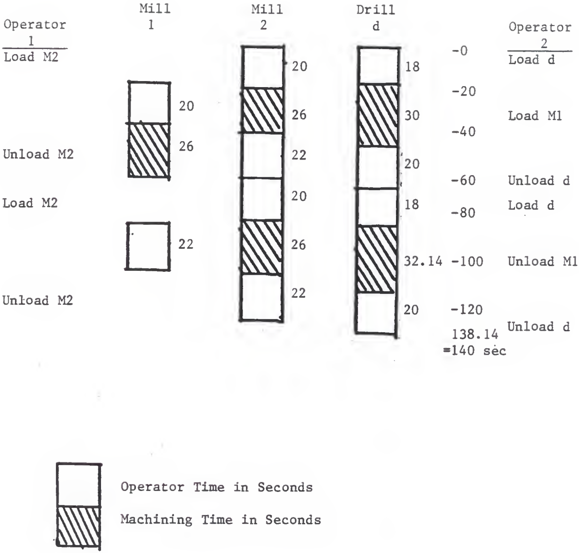

Figure 16: Multi-man-machine chart (two operators in cell)

In summary, the system cost equations are

$$S_{js5\%L} = \$(18.43 + 7.093N + 13.358N^2)$$

$$S_{js10\%L} = \$(18.43 + 4.379N + 6.679N^2)$$

$$S_{js90\%L} = \$(18.43 + 1.966N + 0.742N^2)$$

$$S_{js100\%L} = \$(18.43 + 1.935N + 0.668N^2)$$

$$S_{NC} = \$(12.541 + 2.664N + 0.684N^2)$$

$$S_{CM1} = \$(19.39 + 1.251N + 0.377N^2)$$

$$S_{CM2} = \$(13.695 + 1.1305N + 0.257N^2)$$

Graphical representation of these system costs are shown in the next three figures (17, 18 and 19). Figure 17 is a comparison of the system costs of job shops with different lead times. Figure 18 and 19 are comparisons of the idealized job shop, machining center and cellular manufacturing systems at low and high production volumes respectively.

ERROR CORRECTION

In final preparation of this thesis, a unit conversion error in the inventory carrying rate was detected. The correct unit for the inventory carrying rate should be \$ per \$Hr and not \$ per \$Yr. Thus, the \$3/\$Yr inventory carrying rate should be divided by 2,000 hrs per year to change its unit to \$/\$Hr. By Installing this corrected unit, the quadratic term and linear term in the system cost equations will be changed. The constant term remains the same as before. The new system cost equations are:

$$S_{js5\%L} = \$(18.43 + 1.667N + 6.679\mathrm{x}10^{-3} N^2)$$

$$S_{js10\%L} = \$(18.43 + 1.665N + 3.340\mathrm{x}10^{-3} N^2)$$

$$S_{js90\%L} = \$(18.43 + 1.664N + 3.710\mathrm{x}10^{-4} N^2)$$

$$S_{js100\%L} = \$(18.43 + 1.664N + 3.340\mathrm{x}10^{-4} N^2)$$

$$S_{NC} = \$(12.541 + 2.478N + 3.420\mathrm{x}10^{-4} N^2)$$

$$S_{CM1} = \$(19.39 + 1.088N + 1.885\mathrm{x}10^{-4} N^2)$$

$$S_{CM2} = \$(13.695 + 1.0517N + 1.285\mathrm{x}10^{-4} N^2)$$

Figure 17, 18 and 19 have been modified to reflect these changes.

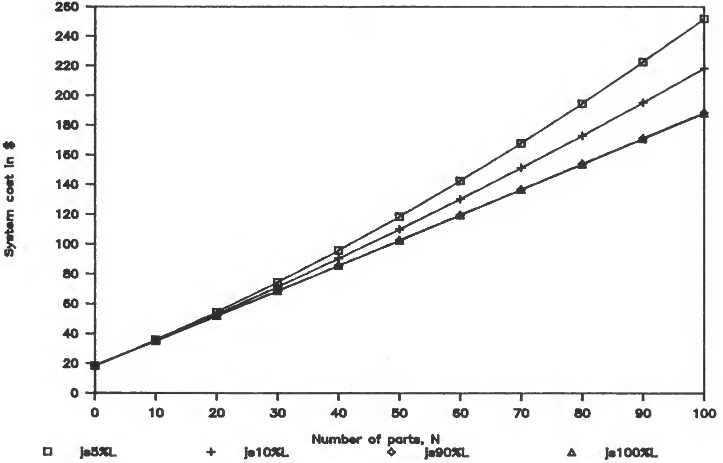

Figure 17: System costs in different job shops.

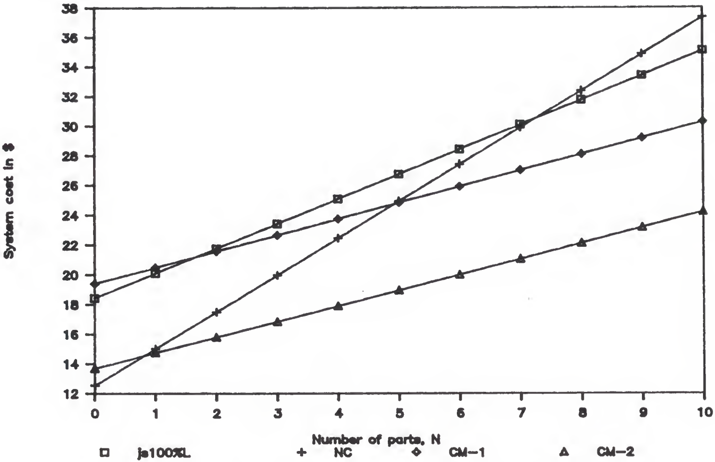

Figure 18: System costs in idealized job shop, machining center and cellular manufacturing at low volume production.

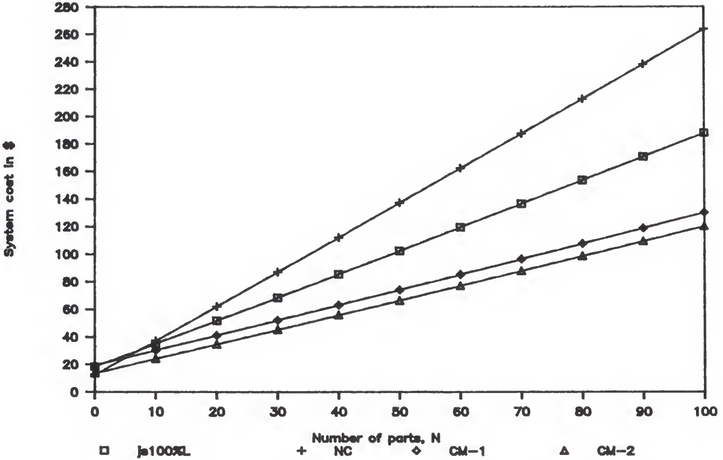

Figure 19: System costs in idealized job shop, machining center and cellular manufacturing at high volume production.

6. CONCLUSION

The applications of sensors, robots, software, Artificial Intelligence (AI), Flexible Manufacturing Systems (FMS), etc, can only solve part of the many manufacturing problems faced by American industries. Some less glamarous practices should not be overlooked. In producing a hypothetical product, this thesis has used three popular manufacturing systems that managers can look into; the job shop, machining center and cellular manufacturing. In order to evaluate the system cost among these alternatives, the basic elements of a manufacturing environemnt have been examined.

The traditional job shop system appears to be the least desirable in this study unless the lead time can be reduced tremendously (say 90% or more, see Figure 17). This reduction is sometimes not attainable. A smaller reduction can be achieved with KANBAN, just in time inventory control or a well planned material requirement planning (MRP) system.

In an idealized job shop (lead time is equal to the total cycle time), the job shop could be equally competitive with the machining center in making very simple parts like the one used in this study. However, the value of parts tied up as work-in-process (WIP) usually make the idealized job shop unattractive unless production volume is high enough to justify it (see Figure 18).

The initial equipment investment for a machining center is very high. But the small setup time and cycle time make the machining center have the lowest startup cost. However, the value of work-in-process (WIP) in the machining center is relatively high as compared with the cellular manufacturing system and the idealized job shop.

The startup cost is highest for the manufacturing cell with one operator. It is because there are three machines for one operator to setup. If the setup time is reduced say by 50%, startup cost can be reduced by the same amount too. Therefore, setup time should be minimized as it is a very important component of manufacturing cost. The value of work-in-process is relatively low in a cell with one operator.

A manufacturing cell with two operators appears to be the best system in this study even at high production levels (see Figure 19). Its startup cost is one of the lowest and its associated WIP value is the lowest.

Setup time is very critical in costing a manufacturing system but WIP value is even more important. The WIP value increases the cost of a production system at a quadratic rate. Even at small production volume, say 100 units per batch, WIP can be the key to selecting a manufacturing system.

Only a very simple product has been considered in this study. It is believed that the cost equations will change for complex parts. Especially for parts that require difficult workpiece or tool manipulations, the machining center might have unique advantages due to its flexibility to maneuver and handle complex workpiece more efficiently. However, this can be left for future studies.

Future studies could also look into the case where more than one product is made. The economic model developed here can be modified and simulated with a computer program.

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COST COMPARISON BETWEEN A JOB SHOP, MACHINING CENTER AND CELLULAR MANUFACTURING SYSTEM

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ABSTRACT

Today's managers can use a variety of methods to analyze and select a proper manufacturing system for their factories. However, most of these system selection techniques emphasize too heavily on non-manufacturing details. Today's managers also tend to choose only the most sophisticated manufacturing technologies they can find and hope that they will solve all their problems. This perception is a result of many factors and it should be avoided.

This study emphasizes three popular manufacturing systems which can be easily adopted. They are: the traditional job shop, machining center and cellular manufacturing system. This study also analyzes the cost of these three systems based on the basic elements of a manufacturing environment which includes the direct labor cost, burden cost, setup time and work-in-process to obtain a final cost. A hypothetical product was chosen. The results show that the traditional job shop system is undesirable. It is inefficient mainly because the level of work-in-process is extremely high. A machining center is reasonably efficient for the simple, hypothetical product used in this study. A manufacturing cell with two operators is considered to be the best system because its system cost is the lowest. Setup time was found to an important cost component, but the

value of work-in-process (WIP) is even more important. WIP increases manufacturing system cost at a quadratic rate. WIP is highest for the traditional job shop, lower for a machining center and lowest for the manufacturing cell. In selecting a proper manufacturing system, the impact of work-in-process cannot be overlooked. For future studies, a mixed product cost model should be developed and the environment should be simulated. The selection decision should also be subject to multi-criteria decision making. Another alternative is to study the system cost variation when complicted parts are introduced.